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Abstract

Category of paper – Case study

Purpose – The purpose is to report on a Danish nanoscience and nanotechnology foresight project carried out in 2004.

Design – The foresight process had the following key elements: 1) Review of international technology foresight projects on nanotechnology. 2) Mapping of Danish nanoscience and nanotechnology. 3) Broad internet survey amongst interested parties. 4) Expert reports, 5) Workshops related to the expert reports. 6) Analysis of the dynamics of innovation within nanotechnology. 7) Survey on hazards and environmental and ethical aspects. 8) Group interviews with members of the public.

Findings –The article reflects on the following methodological issues: 1) Domain classification and its influence on conclusions. 2) The use of statements or hypotheses. 3) Trustworthiness of the foresight process and its recommendations.

Practical implications – Recommendations from the project have already been used in decision-making on R&D funding and in strategic deliberation in publicly funded institutions conducting R&D. Others are expected to be used for decision-making, and some are being discussed in research councils and ministries or are being investigated and developed further. Moreover, the foresight process has created broader awareness of, and debate especially about, the hazardous aspects of nanotechnology among researchers and decision makers.

Value - The article contribute the to the European experiences with national level foresight exercises. The case and the findings are of value for science and innovation policy makers, foresight practitioners and scolars within the field.

Why make nanotechnology a Danish national priority?

Since the 1990s nanotechnology has entered the limelight. Its emergence has been explained in terms of the fact that, in the 1990s, several basic disciplines, such as technical physics, biology and chemistry, developed the ability to operate and manipulate at the nanoscale level. This common scale of operation and manipulation has permitted multidisciplinarity and the combination of scientific paradigms, and this in turn has led to new research areas, new concepts and various possibilities where new products are concerned.

Nanoscience and nanotechnology aim to understand and control the fundamental structure and behaviour of matter at the level of atoms and molecules. They are widely believed to have huge potential benefits in many areas of research and technology and now attract growing government and private investment. At the same time it is recognised that nanoscientific applications are likely to raise new regulatory challenges of a social, health-related, ethical and environmental kind, and that public participation will be a vital part of meeting these challenges.

A technology foresight project was initiated with the purpose of anticipating the range and scope of nanoscientific and nanotechnological development in Denmark over the next 20 years. The aim was to provide a sound basis for cohesive, long-term Danish policy on research, education and innovation. In large countries like the US, Japan and China, annual investments running into many billions of dollars are made across wide areas of nanotechnology. Denmark cannot match figures of that kind. Instead the intention has been carefully to focus on the implementation of targeted and long-term initiatives where Danish economic and societal interests are evident, and where Denmark has particular research and industrial advantages and scope.

The delivery of an Action Plan for Danish nanoscience and nanotechnology containing recommendations for the next few years was the most essential task in the project. Detailed planning for the period running to 2025 was regarded as impractical, because the emerging character of nanotechnology, which is developing very intensively and rapidly on the international scene, makes it necessary to continually re-assess the best opportunities in a Danish context.

A few months after the foresight project started, the Danish government announced the establishment of the High-Technology Foundation. The aim of this new foundation is to strengthen growth and employment by supporting strategic initiatives in high-level technological research and innovation such as nanotechnology, biotechnology, and information and communication technology. The funding for the foundation will be about 27 million euros in 2005, and it is expected to increase over the years. This government initiative attracted a lot of attention to the foresight study on nanotechnology, especially from research environments.

The aim of this article is to both report and reflect on the methodology of the Danish nanoscience and nanotechnology foresight project. The project was undertaken in 2004 by a Steering Group appointed by the Danish Ministry of Science, Technology and Innovation (MTVU, 2004). The Steering Group had seven members and included representatives from nanotechnology industry, nanoscience and social science. A project team from Risø National Laboratory acted as methodological advisers. The secretariat of the Steering Group was The Ministry of Science, Technology and Innovation.

Methodology

Nanotechnology is an emerging technology, and the technological domain is characterised by being in an early, highly exploratory and creative phase in which industrial applications in many areas lie years ahead. Existing nanotechnological enterprises will presumably have business interests in nanotechnology in the future, but it can be safely assumed that a large number of enterprises will appear only in the coming years. Accordingly, it was methodologically very difficult for the Steering

Group to base its work solely on societal and industrial needs. Therefore, it was appropriate to begin with a categorisation of the technology itself and its fields of research.

The overall vision in the foresight project assumed wide-ranging inclusion of relevant actors, players and possibilities. It was hoped that this assumption would produce a societally robust and widely accepted basis for cohesive, far-sighted Danish policy on research, education and innovation in nanoscience and nanotechnology.

Speculative statements about future research and the industrial possibilities and consequences (beneficial and adverse) of nanoscience and nanotechnology were important building blocks in the process. These statements were gathered systematically from international technology foresight projects, from Danish research environments and from expert reports. They were discussed and processed in subsequent workshops, where attention was paid to time horizon, industrial scope, possible adverse consequences, policy instruments, and so on.

The separate components are discussed in what follows below. Their interrelations and sequence are shown in Figure 1.

"Take in Figure 1"

Definitions and mapping

One way of embarking on a technology foresight exercise is to classify the system under examination. In a foresight study, one ideally wants a classification of the domain that is at the same time operational, comprehensive and consistent. This implies a classification of the technological domain that delivers an overview of the object under analysis and identifies boundaries. This initial step of the foresight process is essential, because it has a significant impact on the structure of the subsequent steps of the process.

Any classification of a system embodies a dynamic compromise. Each classification system highlights some points of view and silences others. This is not an inherently bad thing, but it is a decision which must be made transparent to third parties.

As Bowker & Star say (1999, p. 10), "a classification is a spatial, temporal or spatio-temporal segmentation of the world". In an abstract, ideal sense, a classification system will exhibit the following properties: i) there will be consistent, unique classificatory principles in operation; ii) the categories will be mutually exclusive; and iii) the system will be complete. According to Bowker & Star (1999, p. 11), no real-world classification system meets these 'simple' requirements.

The nanotechnology foresight project also ran into difficulties when setting up a classification system. The concepts 'nanoscience' and 'nanotechnology' are very wide fields and not well-defined. Nano-science is a cross-disciplinary area involving physics, chemistry, biology, molecular biology, medicine, materials science and other disciplines. Nanotechnology is said to be generic, emerging, enabling and disruptive. This cross-disciplinary and generic character of the field explains the classification difficulties.

In the Danish nanotechnology foresight project it was decided that the creation of a domain classification enabling an operational process was a high priority. The following was preferred:

- "Nanotechnology is defined as the ability to work at the atomic, molecular and supramolecular levels at a scale of 0.1–100 nm for the purpose of designing, manufacturing, manipulating and applying materials, components and systems with new physical, chemical and biological functional properties. These new properties emerge because of the small scale of the structures, and can therefore not be obtained in other ways. Integration with other scales of length and areas of application will often be essential to technological applications. Nanoscience is concerned with obtaining an understanding of fundamental phenomena, properties and functions at the nanoscale, which are not scalable outside the nanometre domain".

- The domain was divided in three subcategories: a) nanobiosystems, b) nanoelectronics/nano-optics, and c) nanomaterials. These subcategories structured the main activities in the foresight process.

The Steering Group was well aware that these necessary simplifications could require adjustment at a subsequent stage in the process.

Documentation and knowledge provision

Reports, workshops and interviews

Experience from international technology foresight projects on nanotechnology
Internationally, many foresight projects and similar projects on nanotechnology have been conducted. Hence, one of the first steps was to examine these (Luther, 2004). A non-Danish consultant was chosen in order to lend legitimacy to the process – that is, to try to ensure that national interests would not compromise the intention to develop a neutral overview of international experience. The relevance of international conclusions to the establishment of Danish priorities was assessed later in the process, especially during the preparation of expert reports.

Mapping of Danish nanoscience and nanotechnology
Information on Danish nanoscience and nanotechnology was gathered via questionnaires that were sent to institutions and enterprises. A list of Danish publications in the area was also produced, using a European database (Strange & Dannemand Andersen, 2004).

Broad survey amongst interested parties
The views of a wide circle of interested parties in Denmark were obtained in an Internet-based qualitative survey. The questions covered: a) name and position in organisation; b) principal occupation; c) statements on development trends and scientific breakthroughs; d) initiatives and instruments; e) industries and fields of application; f) other matters relevant to nanoscience and nanotechnology. A total of 303 questionnaires were sent out, of which 133 were returned completed (Dannemand Andersen et al., 2004). In all, 59% of the replies came from "public research" and 28% from "industry"; the remaining 13% came from consultancies and others. There were 175 statements on nanobiosystems, 123 statements on nanoelectronics/optics and 167 statements on nanomaterials.

Expert reports
A key part of the work on the foresight project was the preparation of three expert reports: nanobiosystems (Wengel et al., 2004), nanoelectronics/nano-optics (Stubkjær et al., 2004) and nanomaterials (Feidenhans'l et al., 2004). Each report was produced by a group of four experts appointed by the Steering Group. The purpose of the reports was, first, to analyse the area concerned; and second, to provide the basis for a subsequent workshop on each area. The reports contained: a) a description of the technology field; b) an assessment of the scientific, technological and market possibilities; c) an assessment of Danish strengths; d) an assessment of the political conditions with regard to research, education and innovation, and the instruments of research, educational and innovation policy; e) an overview of the general environmental, hazard-related and ethical aspects of the area.

Technology-oriented workshops
For each of the three subcategories a workshop was organised with approximately 20 participants. The participants were personally invited and represented the most important players and specialist competences in the area. The specific purposes of the workshops were: 1) to comment on and discuss the expert report, 2) to discuss technological and research priorities, and 3) to examine research, education and innovation policy instruments.

Report on the dynamics of innovation
The report describes mechanisms, processes and dynamics that characterise "emerging" technology and science environments and innovation processes. The theoretical basis of the description was partly derived from ideas set out in Value-Creating Research, Technology and Market Networks (Karnøe, 2004).

Report on hazards and environmental and ethical aspects
The report summarises international literature (including that on the Internet) concerning potential applications of nanotechnology and the consequences these applications might have for humans and the environment (Christiansen, 2004).

Group interviews with members of the public
The (positive and negative) attitudes of ordinary citizens to the possibilities of nanotechnology are an important input to policy commitments in this area. A survey of "Public Attitudes to Nanotechnology" was carried out. It involved 29 interviewees from the Copenhagen area and took the form of four group interviews, followed by completion of a questionnaire (Pedersen & Vincentsen, 2004).

The outcome of these reports, workshops and interviews are summarised in the sections below.

Nanotechnological research in Denmark

Generally, Danish research environments are internationally strong in a number of areas that are central to nanotechnology. Examples are niches in quantum physics, biochemistry, optoelectronics, scanning probe microscopy and X-ray diffraction/spectroscopy. In relation to the countries normally compared with Denmark, Danish scientific production measured in number of publications lies in the midfield. In certain areas, Danish nanoscience is at the forefront.

It is also potentially a Danish strength that major breakthroughs in nanoscience and nanotechnology are expected to take place on the borders between traditional scientific disciplines. The dynamic development of nanotechnology will therefore require collaboration reaching from areas such as physics, chemistry and materials science to areas such as biology, molecular biology and medicine. This will necessitate cross-disciplinary scientific collaboration and thinking. Denmark is well equipped for cross-disciplinary research. Such interaction is an established feature of many of our existing research networks. Moreover, Denmark is a small country with a flat societal structure, and this permits short decision paths and great flexibility, both of which are prerequisites for a vibrant innovative environment.

Danish universities have been quick to start offering degree courses in the nano field, at both BSc and MSc level. In Denmark, as in other countries, it has become difficult over recent years to interest young people in studying for degrees in physics, chemistry, and engineering sciences. However, several universities have found that courses with the 'nano' in their titles attract new students.

Danish research is highly international and involves wide participation in international networks, especially within Europe. Hence, there is a considerable volume of exchange between young researchers in Denmark and other countries.

Lastly, over recent years considerable resources, both public and private, have been invested, in Denmark, in production and clean-room facilities. These resources will be available in the coming years for use in research and by industry.

It seems to be a weakness that, by international standards, the research culture in Danish universities is not particularly industry-oriented. This is partly attributable to the separation in Denmark between the engineering sciences and basic or pure scientific research. Danish nanoscience has concentrated on the descriptive characterisation of natural phenomena. Traditionally, much less attention has been given to synthesis – i.e. to the translation of our understanding of natural phenomena into the creation of new materials and products. This situation has also hampered the development of a basis for strong, productive interplay with industrial enterprises. However, there is an emerging tradition of commercialisation of research results, the handling of patents, and other Intellectual Property Rights in Danish universities.

Often, the Danish innovation system also lacks the necessary culture and the people specialised in knowledge transfer between universities and industries. Business and management skills that Danish scientists and research establishments do not generally possess are required. In comparison with other countries, the mobility of researchers between research establishments and industry in Denmark is low.

Lastly, characteristically, Danes find it difficult to undertake major, well-focused initiatives. It is perhaps particularly difficult to give some areas a high priority while placing others lower on the list. The marked culture of consensus in Denmark, and the sometimes inadequate knowledge base on which research and technology policy decisions have to be made, means that investment often takes the form of allocations of small sums to a number of projects. There is no Danish tradition of as it were ‘picking the winners’ or backing an elite prospect.

Nanotechnology and the dynamics of innovation

Nanotechnology can produce enormous leaps of technological progress and thereby redefine familiar technological platforms for many enterprises. Like other revolutionary technologies, nanotechnology therefore gives rise to “creative destruction”. It is competence-destroying, as it challenges the ability to create value on established knowledge and technology platforms. However, at the same time, it offers completely new development opportunities both to existing enterprises and, in particular, new enterprises.

The creative and transformational power of nanotechnology originates to a large extent in the research and education system. This is because, first, many research laboratories are developing new knowledge and interesting nanotechnologies; and second, nanotechnology is in general being strengthened by an acceleration in the number of experiments, the circulation of articles, prototypes, the exchange of researchers, the training of postgraduates, and so on.

Potential for innovation lies both in adding nanotechnology to existing functions and in combining knowledge in completely new ways in the new technological fields that emerge. In the latter case, a large investment in market and product development is required before the commercial rewards can be realised.

It is an important characteristic of nanotechnology that it is cross-disciplinary and challenges existing boundaries between physics, chemistry, materials science, molecular biology, biology and medicine. The traditional lines of demarcation between disciplines break down here. Many new competences will be cross-disciplinary in character until they become established and set new lines of demarcation. Efficient exploitation of nanotechnology therefore requires the ability to take an all-inclusive view, and to be at ease working freely across traditional disciplinary boundaries and in new knowledge networks. This means that major Danish initiatives implemented as part of our policy on nanotechnological research, education and innovation cannot be organised as they would be in traditional research disciplines: new patterns of organisation are needed.

It would be natural to gather different combinations of related, high-priority focus areas together in cross-disciplinary nanotechnology centres for strategic research and innovation. Organisation around such nanotechnology centres could lead both to the reinforcement of existing industrial clusters and the creation of new, desirable cluster effects with the formation of new dynamic knowledge networks.

Hazards and environmental and ethical considerations in the application of nanotechnology

Alongside the expected benefits, there is also considerable uncertainty. Entirely new, imperfectly understood hazards attach to nanotechnology. There are still very few studies of the potential undesirable effects of nanotechnology. However, owing to the great attention the area receives, a large number of such studies are now being made around the world. Nanotechnologies are generic technologies. They have special features that distinguish them from many other technologies that impact on health and the environment:

- Nanotechnology is an emerging technology, and this makes it necessary to place special emphasis on the assessment of uncertainties relating to different scenarios and development trajectories.
- Nanotechnologies have a wide area of application. Their ubiquitous and horizontal nature leads to a far-reaching spread of nanomaterials in products and the environment, and this makes them difficult to control.
- Due to their size, nanomaterials have different properties from bulk material. The biological behaviour and mobility of ultrafine particles differs from that of larger particles. Here there is not a linear relationship between mass and effect (Jong, 2004).
- One area of risk connected with nanotechnology relates to the ‘invisible’ size of the particles being developed. Such particles could accidentally enter into the food chain, initially causing damage to plants and animals and eventually becoming a hazard to humans (Malsch et al., 2004, p. 60).
- Another risk associated with nanoparticles arises from their large surface area, crystalline structure and reactivity. These features could facilitate transport in the environment or lead to harm through interaction with other elements (Malsch et al., 2004, p. 60).

The development of nanosensors and similar devices may open up completely new opportunities for surveillance and control. However, these opportunities will raise ethical issues – issues connected, for example, with nanoscale surveillance equipment that can be built in anywhere but cannot be seen with the naked eye. Equally, the development of self-organising and self-learning structures has a very long time-horizon, but its consequences are so great that its ethical impact will need to be examined in good time.

It should be noted that there appears to be considerable ignorance among the Danish population as a whole about nanotechnology and its potential consequences. The attitude seems to be that Denmark should be a leading country in the development and application of nanotechnology but also adopt an attitude of healthy criticism and conduct serious research into the hazards and ethics of nanotechnology.

There is a desire among the public to see nanotechnology used for purposes that offer wide benefits with due regard for people and the environment. Examples include pollution control, climate change, poverty in developing countries, and disease. Responsibility for the potentially adverse consequences of nanotechnology, and any legislation governing its handling, must be precise and transparent. It is important that applications that are evidently dangerous should be blocked or subjected to regulation with strict controls.

Action Plan

The Steering Group’s vision is that towards 2020 Denmark will be among world leaders in mastery of nanotechnology within selected areas and its industrial application. This should secure increased growth and employment, and answers to important societal needs.

The purpose of the Action Plan was to identify areas and prospects that may be advantageously pursued by Danish policies on research, education and innovation. In selecting focus areas within the Danish nano programme, the Steering Group adopted the following three criteria:

- *Industrial and societal relevance.* Focus areas must be relevant both to Danish enterprises and society in general; and to both existing enterprises and the seeds of future enterprises.
- *Research strengths and/or potentials.* High-priority focus areas will preferably be based on existing scientific and technological excellence in Denmark (or, failing that, on the possibility and the will to create such excellence), together with great potential for continued scientific development linked to technological development. Critical mass must be achieved, as well as favourable conditions for the kind of work (across traditional boundaries between the sciences) that is required by the commercialisation of nanotechnology.
- *Global industrial, research or societal importance.* There may be areas that have not previously been cultivated by Danish research or industry but are thought likely to become so strategically important in the future that they must nevertheless be prioritised upwards. Such areas may have markets that will grow to an enormous global volume. They may, over time, threaten or suppress known technology platforms.

On the basis of these criteria, the Steering Group identified seven high-priority areas of technology. These areas offer Denmark good prospects of technological development, industrial application and societal benefits (in non-prioritised order):

- Nanomedicine and drug delivery
- Biocompatible materials
- Nanosensors and nanofluidics
- Plastic electronics
- Nano-optics and nanophotonics
- Nanocatalysis, hydrogen technology, etc.
- Nanomaterials with new functional properties

In addition, there are of course a large number of other nanotechnology areas that offer exciting opportunities in the long term. These may merit smaller initiatives assessed partly on the accessibility of strong relevant research environments and partly on the commercial prospects they offer. Self-organising systems, semiconductor quantum points, molecular electronics, nanotubes and nanofibres, spintronics, magnetic nanomaterials and thermoelectric materials are just a few examples of such areas.

Recommendations on research, education and innovation policy

The objectives relating to societal usefulness of nanotechnology concern energy and the environment, food products, health, and the general development of industry and welfare. Their pursuit requires a political commitment to the provision of strong backing for research in nanoscience and nanotechnology. Another requirement is the development of high technology in Danish enterprises to ensure that they have the skills, the workforce and the capacity to translate the new breakthroughs in nanotechnology into products and positioning in the market. This development can be given a significant boost by means of a coordinated strategy for the promotion of nanotechnology.

Targets, within a 20-year time-horizon, for the nanotechnology promotion policy should be:

- Nanotechnology widely used in Danish enterprises – both large and small – and in many different fields of application and sectors of industry.
- A tier of new small and medium-sized high-technology enterprises based on nanotechnology.
- A smaller number of large enterprises whose business is based on nanotechnology.

Coordinated strategy on nanotechnology will need to include a broad range of initiatives. The Steering Group offered the following recommendations:

1. Prioritise technology areas.
2. Create interplay between nanotechnological research and high tech industry.
3. Establish nanotechnology centres for strategic research and innovation.
4. Increase numbers of higher graduates and researchers.
5. Spread nanotechnology widely amongst Danish enterprises.
6. Attend to potential hazards, and to health-related, environmental and ethical considerations.

1. Prioritise technology areas

Support should be given to technology areas in which Danish enterprises and research environments are at the international forefront and have good prospects of translating the results of nanotechnological and nanoscientific research into practical industrial applications. Seven high-priority technology areas were presented, each of which offers many and very varied possibilities. Besides these seven, there are a large number of areas where smaller initiatives and projects ought still to be financed. The Steering Group considered it vital that initiatives within the high-priority areas are not at the cost of independent research in nanoscience and nanotechnology – either inside or outside the seven high-priority areas.

2. Create interplay between nanotechnological research and high tech industry

The Steering Group distinguished three types of initiative that can be expected to further nanotechnological and nanoscientific research and the development of high technology in industry over the coming years. The volume of finances and resources to be allocated to the initiatives varies according to the anticipated potential of the research and the time-horizon for any industrial breakthroughs:

- *High-priority initiatives*: The initiatives should be cross-disciplinary in their scientific and technological character, and they should be organised outside the usual discipline-oriented environments. They should gather different research disciplines within the same technological initiative. They should also be generic in character, so that they can be directed towards several different industrial applications. There should be at least five postdocs for each initiative. The initiatives should attract grants for actual running costs in the order of 2 to 3.5 million euros a year over a ten-year period.
- *Visionary initiatives*: Visionary initiatives are proposed in areas with potential over the slightly longer term. They should also be cross-disciplinary and generic. The Steering Group recommends that these initiatives should attract grants for running costs in the order of 0.7 to 2 million euros a year over a five- to ten-year period. There should be a focus on postdocs who aim to start a business or obtain a post in industry after completing their postdoc appointment.
- *Exploratory projects*: Exploratory projects should be initiated in exciting new areas of nano-science where the potential nanotechnological applications lie relatively distant in the future. Projects should be arranged as research or innovation projects in which researchers aim from the beginning to start up high-tech businesses. The project size should be 0.4 to 0.7 million euros a year over 2-3 years.

3. Establish nanotechnology centres for strategic research and innovation

National investment in nanotechnology and nanoscience should take the form of a concentrated programme that creates entities with real international impact. The Steering Group recommended that two national nanotechnology centres for strategic research and innovation be created. These must have the critical mass to become international scientific and technological leaders in their field. It is important that the mutual agenda-setting between industry and research is emphasised in the research at the centres. It is also important for the centres to have strong links with educational environments. Each of these centres must grow to a size meriting a budget, for their activities, of at least € 15m a year.

4. Increase numbers of higher graduates and researchers
Increased commitment to nanoscience and nanotechnology over the coming years requires a sufficient number of qualified MSc graduates and researchers to be available. The training of graduates at MSc, PhD and postdoc level is an important means of effecting knowledge transfer between enterprises and research institutions.

5. Spread nanotechnology widely amongst Danish enterprises
Danish industry must be able to participate widely in the industrial revolution brought about by nanotechnology. Special efforts must be made to provoke interest, among both new and established enterprises, in the possibilities offered by nanotechnology. As mentioned above, this will be an important part of the function of the proposed nanotechnology centres for strategic research and innovation.

6. Attend to potential hazards, and to health-related, environmental and ethical considerations
Serious attention must be given to studies of the potential health hazards and the environmental and ethical effects associated with nanotechnological industrial processes and materials and other applications of nanotechnology. The Steering Group recommended that grants be coupled with a requirement to prepare a risk assessment covering production, use and subsequent disposal, and a comparison with alternatives. Denmark should urge the EU to take an active role in this area. The EU should help to coordinate and gather information from the many risk assessments that are being undertaken around the world.

Robustness

A seminar with interested parties was arranged at which a first draft of the Action Plan was presented. The purpose of the seminar was twofold: first, to raise the profile of the foresight exercise and nanotechnology; second, to assess reaction, from as many Danish parties with interests in nanoscience and nanotechnology as possible, on the key points of the foresight and the Action Plan. The seminar was held on 15 September 2004; about 200 participants attended. Feedback from the participants was mainly constructive and positive. Of course, there were disagreements over details, but the seminar can fairly be said to have enjoined and expressed wide support for the Action Plan.

Follow up on the foresight report

After publication, the recommendations of the foresight report were disseminated to individuals in the target group of the foresight. The chair of the Steering Group presented results and recommendations to the Minister of Science, Technology and Innovation, chairs of the Danish research and innovation advisory and grant-awarding system, and representatives from universities, technology service institutes and national research laboratories.

Some of the recommendations have already been used in decision-making on R&D funding and in strategic deliberation in publicly funded institutions conducting R&D. Others are expected to be used for decision-making, and some are being discussed in research councils and ministries or are being investigated and developed further.

Moreover, both the foresight process and the final report have created broader awareness of, and debate about, the hazardous aspects of nanotechnology among researchers and decision makers. The relevant authorities and institutions are now examining these questions more seriously.

Summing up - lessons learned

Domain classification and its influence on conclusions

The first step was domain classification, the aim being to outline the playing field and to set out the content of the problem to be analysed. Domain classification provides a platform for discussion and focuses the technology foresight study. The problem must be clearly in focus and linked with precise objectives in order to avoid becoming irrelevant to the problem owner. The discovery that such focus is not possible is often an indication that the problem's content and concepts are not clear to anyone, which can lead to confusion, frustration and conflict in the subsequent parts of the process.

As discussed earlier, domain classification has a significant impact on the structure, and consequently the outcome, of the entire foresight process. The line, or course, of this impact is illustrated in Figure 2 below. The left-hand column is the domain classification worked out in the initial stage of the process. The separation of the three major categories (nanobiosystems, nanomaterials and nanoelectronics) formed the basis for preparation of an expert report in each category. The second column from left contains the subcategories emerging from the broad survey and expert reports. These subcategories played a significant role in the selection of high priority areas, because they were the input to the focusing process in the expert workshop (third column from left). The column to the far right contains the seven high-priority areas of technology in the Action Plan together with a list of promising further areas.

"Take in Figure 2"

For this project the domain classification was less than straightforward, because nanotechnology is a generic, emerging technological domain. Our experience with the domain classification adopted in this project was that several of the experts involved accepted the overall mapping but had comments on the details, especially in the nanomaterials domain. The most valuable outcome was the fact that the classification provided a common basis for discussion.

Statements

A basic concept in the process was the formulation of statements as principal elements. According to Loveridge et al. (1995, p. 8) "… *a statement is a concise expression of an event, achievement or other phenomenon upon which views are sought. In as few words as possible, an unambiguous expression of what the questioner has in mind must be achieved, which incorporates any key conditions but which excludes separate issues that warrant one or more additional topics*".

The intention of the process design was to build the foresight on a systematic collection of statements or hypotheses about the scientific and commercial potentials of nanotechnology within a time horizon of 20 years. Subsequently, these statements/hypotheses were to be exposed to critical scientific discussion. The lesson learned was that the experts and actors were not familiar with the approach to thinking found in statements. Typical remarks were: "it is impossible to predict the future" and "real science cannot be predicted – if it could it would not be science". To mitigate this anticipated reaction, the term 'hypothesis' was used in parallel with the term 'statement'. The hope was that feelings of unease, within the nanoscience community, about the intention behind the statements would thereby be minimised.

The expert papers show that the project group extracted 91 statements; a further 149 were extracted from responses to the internet survey. Approximately a third were in each of the three main groups. At the workshops, the statements were commented on, and a *real-time Delphi* questionnaire was filled in at the end of each workshop.

The overall classification was settled by the end of the process. The project group selected 32 statements to illustrate the visions and possibilities.

Statement no.		Before 2010	2011-2015	2015-2020	2021-2025
	Nanomedicine and drug delivery				
1	Practical application of intelligent systems in drug delivery systems which monitor the state of cells in the body and report if, e.g., cancer or small blood clots arise.				
2	Development of self-assembling nanocapsules consisting of functionalised polymers for cell-specific recognition, controlled release of active substance and concealment of the particle from the body's immune system.				
3	Development and design of biocompatible materials for drug delivery, solving problems of slow release, passage of the blood-brain barrier, etc.				
4	Development of new types of drugs (e.g., self-assembly of peptides and/or DNA strands into bioactive complexes) based on nanoscale interactions and structural assemblies.				
	Biocompatible materials				
5	Development of nanobiotechnology for the repair of defective neurons by the application of electrically conducting nanostructures.				
6	Practical application of synthetic surfaces with biological properties for use in implants, prostheses and medico-technical equipment in long-term contact with human cells or tissue.				
7	Practical application of nanodesigned surfaces that promote or inhibit adhesion of, e.g., bacteria or algae (antifouling).				
	Nanosensors and nanofluidics				
8	Practical application of NEMS (nano-electro-mechanical systems) for the selective detection of specified molecules or cells, measurement of heat generation, measurement of binding energies, etc.				
9	Development of very efficient, distributed sensor systems based on a combination of CMOS chips and NEMS sensors, that supply the measured information using wireless technology in, e.g., environmental monitoring, process control, indoor climate control and traffic safety.				
10	Practical application of "lab-on-a-chip" systems based on nano-optics and nanofluidic liquid handling systems for point-of-care diagnostics.				
11	Practical application of implanted sensors, e.g. for monitoring infections.				
	Plastic electronics				
12	Practical application of polymer electronics (displays and sensors) integrated into packaging, which will make it possible to monitor the general condition and history of goods during transport and storage.				
13	Practical application of polymer transistors integrated into single-use equipment for analytical purposes in primary health care.				
14	Practical application of multicoloured plastic displays instead of liquid crystal displays.				
15	Practical application of RFID tags based on polymer FETs.				
16	Practical application of solar cell technology based on polymer electronics and polymer optics.				
	Nano-optics and nanophotonics				
17	Practical application of microstructured fibres in their longitudinal direction for use in high-power lasers (welding, light sources in large displays, etc.), super-continuum-generating units and special uses in optical communication systems, switches, etc.				
18	Practical application of compact, low-price nano-/microstructured plane components with integrated optical circuits based on photonic band gaps. Application in fibre-to-home and sensors.				
19	Development of new sensors or optical switches based on filling (with liquids, coatings or liquid crystals) of the fine structure in optical crystal fibres.				
20	Practical application of simple signal processing (such as modulation, wavelength conversion, four-wave mixing and optical conjugation) based on PBG structures with built-in optical elements of great nonlinearity.				
	Nanocatalysis, hydrogen technology, etc.				
21	Practical application of tailored catalysts and other functional nanomaterials in *in situ* methods, theoretical methods, and similar.				
22	Practical application of hydrogen storage in chemical form, e.g., methane, methanol or ammonia or in the form of metal hydrides, using new materials based on nanotechnology/nanoparticles.				
23	Practical application of new, cheaper SOFCs and PEM fuel cells with long life in realistic conditions.				

24	Development and improvement of catalysts based on natural enzymes, efficient at low temperatures and pressures.	
25	Practical application of nanosystems for specific catalysis for the breakdown of pollutants in nature using preorganisation of reagents, catalysis and product release.	
	Nanomaterials with new functional properties	
26	Practical application of alloys or ceramic materials that crystallise with very small grain size (high strength and good workability) for high-value products, from the micro to the macro scale, from implants to sports equipment.	
27	Development of nanocomposites which are stronger, and have better thermal stability and chemical resistance, than pure polymers. Improvements in corrosion resistance, sound absorption, consolidation of manufactured pieces and recyclability.	
28	Practical application of woven and non-woven textiles made from polymer fibres in the textile and hygiene industries.	
29	Development of new types of coatings with built-in functions, achieved by building in a chemical functionality, through nanoparticles, or through a nanostructured topology.	
30	Practical application of block copolymers for the development of self-repairing surfaces (the material itself ensures that it is the correct functional block that is exposed).	
31	Practical application of nanoporous materials as filters in the food and drink industry.	
32	Development of thermoelectric materials with radically improved properties for cooling and energy production, based on nano-sized structures.	

Trustworthiness of the foresight process

Input from various sources is essential in technology foresight studies in order to identify a range of viewpoints, agreements and controversies. It is important that, on the one hand, the recommendations of the foresight study are based on high quality and reliable documentation, and on the other hand, the process is regarded as legitimate by a broad group of interested and affected parties.

The aim of the mapping of Danish nanoscience and nanotechnology, and the subsequent broad survey of interested parties, was intended, first, to provide an overview of actors and activities, and second, to use this as a basis for distributing the questionnaire. The intention was to identify activities and viewpoints, and to establish a comprehensive process giving a large number of actors the opportunity to present their views. In all, 133 respondents out of 303 (about 44%) returned the questionnaire. This was considered to be a satisfactory response.

The expert reports and workshops were key documents and information sources in the foresight process. Each report was produced by a group of four experts appointed by the Steering Group. Each group contained members from research as well as industry.

The nomination of experts to participate in the workshops was considered carefully. The participants were selected and personally invited by the Steering Group. They were selected with the following considerations in mind:

- it is crucial to identify experts who are both visionary and actively involved in the field
- there should be 5-7 researchers from engineering or natural science; 5-7 representatives from industry; 1-2 researchers from social science; and 1-2 from the scientific press
- wide distribution across age, sex, province, size and type of institution/enterprise is desirable

It is also important, in workshops, to make attendance attractive and interesting to experts. Experts are busy people, and their willingness to participate and contribute to technology foresight studies depends on their personal interests and sense of public spirit. In this foresight study, the establishment of the High-Technology Foundation led to a strong focus on funding for nanotechnology. This made the workshops attractive to experts, who hoped, by attending, to have an influence on the content of the recommendations and Action Plan.

Looking back at the experiences and lessons learned from genetic engineering, it is possible now to see that, in this particular foresight process, there was a serious intention to focus on normative aspects of technological development. This was done through an expert report on ethics, risk, the environment and health; and through group interviews with members of the public. It appears that these distinctive activities have helped to set a broader research agenda for nanoscience and nanotechnology, and that the foresight project has been an eye-opener to many researchers in nanoscience, especially when it comes to risk issues raised by nanotechnology.

Finally, the first draft of the Action Plan was presented to, and discussed by, a group of no fewer than 200 interested and affected parties at a seminar. Those attending this seminar had an opportunity to present verbal or written opinions.

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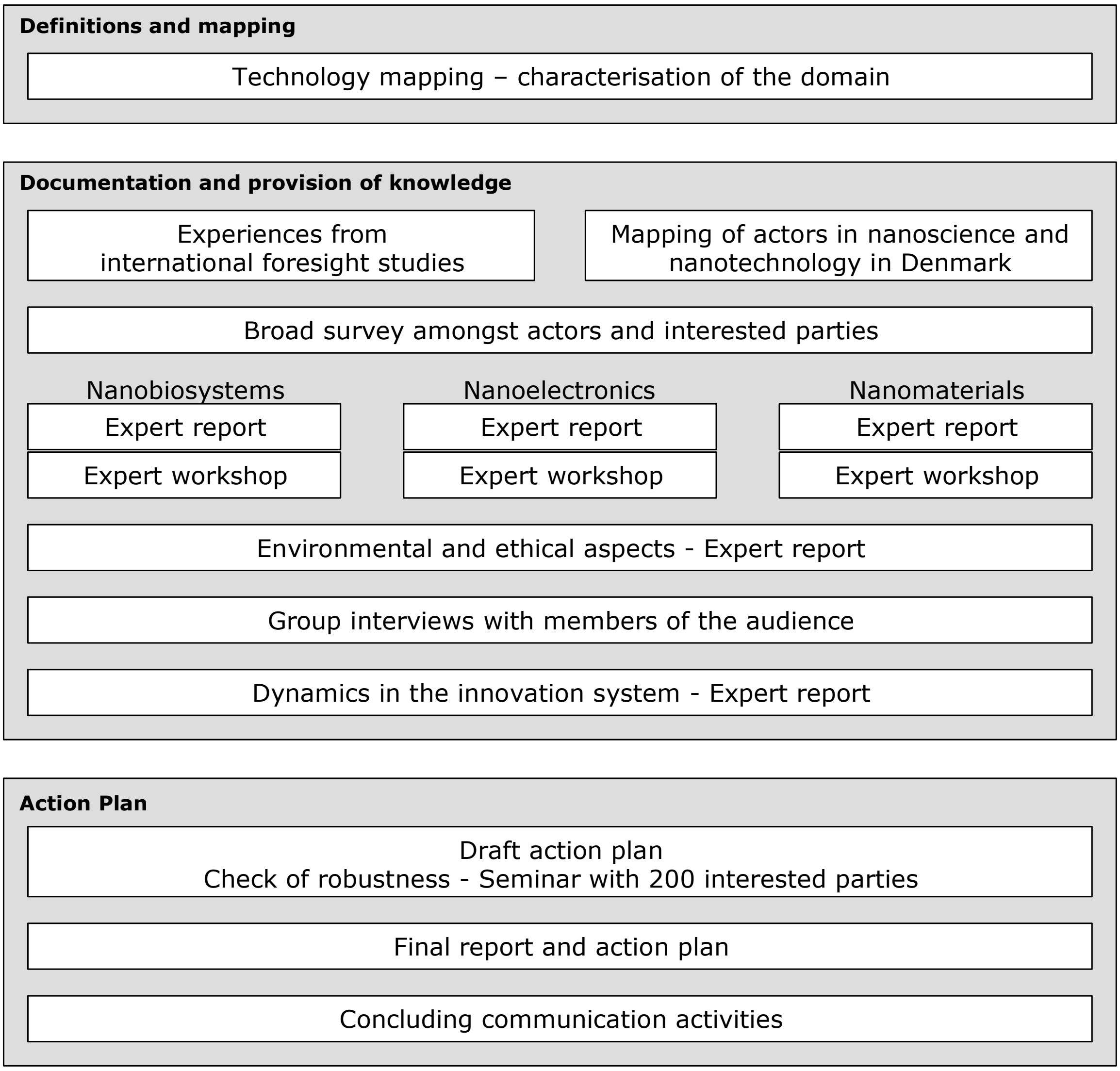

Figure 1. Overall process diagram.

PROCESS →

DOMAIN CLASSIFICATION	TOPICS PROPOSED IN EXPERT REPORTS AND BROAD SURVEY	TOPICS PRIORITISED BY THE EXPERT WORKSHOPS	ACTION PLAN
nanobiosystems	drug delivery and drug targeting nanomedicine nanobiosensors nanofluidics nanoelectronic nanocomputers nanomotors biocompatible surfaces catalysis and synthesis advanced nanorobots interfaces to life diagnostics membranes cellular level	drug delivery and drug targeting nanobiosensors biocompatible surfaces, incl. interfaces to life catalysis and synthesis	
nanomaterials	nanophase & nacocrystallinic materials - termoelectric materials - plastic electronics - polymers - spintronics - nanostrctured surfaces nanoparticles - catalysis - fuel cells - pigments - magnetic nanoparticles coatings and surfaces nanofibre and composites nanotubes nanoporous materials nanostructured materials self-organising systems characterisation, analysis and modelling	nanoparticles – catalysis nanoparticles – energy nanophase & nacocrystallinic materials polymers thermoelectric materials and spintronics coatings and surfaces characterisation, analysis and modelling	High priority areas nanomedicine and drug delivery biocompatible materials nanomaterials with new functional properties nanocatalysis, hydrogen technology, etc. nanosensors and nanofluidics plastic electronics nano-optics and nanophotonics Promising areas in the long term self-organising systems semiconductor quantum points molecular electronics nanotubes and nanofibres spintronics magnetic nanomaterials thermoelectric materials
nanoelectronics	nanooptics and optical systems molecular electronics plastic electronics organic electronic nanosensors semiconductor quantum points lithography characterisation and certification electronic components	nanooptics and optical systems plastic electronics nanosensors	

Figure 2. Line of impact from domain classification to Action Plan